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During the 1995–96 year of the research program on "Microwave and Transport Studies of Superconducting Films of YBCO and Fullerenes," the effort was focused on several projects. The main highlight was a collaborative study of the nonlinear microwave properties of superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) which was carried out with researchers at Rome Labs and the MIT Lincoln Laboratory. During this year Nathan Belk completed his Ph.D. thesis entitled "Electronic Transport and Magnetic Properties of Disordered High-T_c Materials." Joe Habib made significant progress with his study of microwave losses in individual Josephson junctions. A new graduate student, Chris Lehner, who is an Army Captain, joined the group on assignment from the US Army, and is working on the modeling of microwave losses in superconducting circuits. Continued progress was made with the use of femtosecond optics to study superconducting and associated phenomena in alkali metal doped C_{60} materials.

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FINAL

~~Annual~~ Technical Report

to the

Air Force Office of Scientific Research

for research on

MICROWAVE AND TRANSPORT STUDIES OF SUPERCONDUCTING FILMS OF YBCO AND FULLERENES

AFOSR Agreement #F49620-93-1-0160
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Annual Report

Abstract

During the 1995–96 year of the research program on "Microwave and Transport Studies of Superconducting Films of YBCO and Fullerenes," the effort was focused on several projects. The main highlight was a collaborative study of the nonlinear microwave properties of superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) which was carried out with researchers at Rome Labs and the MIT Lincoln Laboratory. During this year Nathan Belk completed his Ph.D. thesis entitled "Electronic Transport and Magnetic Properties of Disordered High-T_c Materials." Joe Habib made significant progress with his study of microwave losses in individual Josephson junctions. A new graduate student, Chris Lehner, who is an Army Captain, joined the group on assignment from the US Army, and is working on the modeling of microwave losses in superconducting circuits. Continued progress was made with the use of femtosecond optics to study superconductivity and the associated phenomena in alkali metal doped C_{60} materials. In this report we review the progress that was made on each of these projects.

Microwave Properties of High T_c Superconductors

During the 1995–96 year our group worked on three projects of relevance to the microwave properties of high T_c superconducting thin films.

1. Microwave Vortex Dynamics

After completing studies of the complex surface impedance of YBCO thin films in the linear microwave power regime using a stripline resonator over a wide range of temperatures from 5 K to 90 K, covering frequencies from 1.2 GHz to 22 GHz, and magnetic fields from 0 to 4 Tesla [#1,#2], we focused our attention on studies of the microwave vortex dynamics in the nonlinear regime [#3]. The nonlinear surface impedance (power dependence) was thus measured as a function of frequency, temperature, and external field. This work constitutes a substantial part of Nathan Belk's Ph.D. thesis [#8,#9].

Increased microwave current increases the amplitude of oscillation of the pinned vortices, and when the amplitude of oscillations is large enough, the vortex can be driven from the potential well in which the vortex is pinned. The measurements show that increases in microwave current lead to increased losses as expected. However, the amplitude of vortex motion required for the losses to increase is smaller than a simple pinning model would predict. In fact, Nathan Belk has been able to explain the observed results for the change in R_s and in X_s in the nonlinear regime using the same model as was used used to explain the linear vortex dynamics [#1]. The

mechanism for both the linear and nonlinear regimes assumes the existence of a large number of metastable bound vortex states, separated by energy barriers U_b whose magnitudes extend from $U_b \sim 0\,\mathrm{K}$ to several hundred K. The dominant contribution to R_s arises from vortex transitions between these states. This explanation of the power dependence thus provides further corroboration for the model used to explain the linear in-field surface impedance, which was a focus of last year's report, and constitutes another substantial part of Belk's thesis.

It has been proposed that a simple and valuable way to differentiate among the various mechanisms giving rise to a nonlinear surface impedance is examination of the quantity $r = \Delta X_s/\Delta R_s$ as a function of the microwave magnetic field H_{rf}, where $\Delta X_s(H_{\mathrm{rf}})$ and $\Delta R_s(H_{\mathrm{rf}})$ are the changes in surface reactance and resistance, respectively. For the case of a microwave resonator, the quantity r can be shown to be related only to the experimentally determined quantities $\Delta Q(P)$, the change in quality factor as a function of power P, and $\Delta f_0(P)$ the change in resonance frequency, since $\Delta X_s = -\Gamma 2\Delta f/f_0$ and $\Delta R_s = \Gamma\Delta(1/Q)$ where Γ is a geometric factor that is the same for both and thus cancels in the ratio. While the usual plots of R_s vs. H_{rf} and X_s vs. H_{rf} are useful, the r values provide a more direct comparison with experiment, because R_s, X_s, and H_{rf} are derived quantities, while Q and f_0 are directly measured, and P is a known experimental parameter. Thus we can write $r(H_{\mathrm{rf}}) = r(P)$. Experimental calibrations accounting for cable or probe losses are completely eliminated from consideration when one considers the r values. The various physical mechanisms that have been proposed to describe the power dependence in high-T_c superconductors each have characteristic r values. Not only are the magnitudes of the r values different, but also the frequency and temperature dependence have characteristic signatures. Thus, the measured r values can be used to differentiate among these mechanisms, especially by measurements on r as a function of frequency and temperature. Nathan Belk obtained some results for r in connection with his thesis work. Further work on this topic is in progress and will be pursued in the coming year.

2. Contribution of Josephson Junctions to Microwave Losses

To study the connection between Josephson junctions and microwave losses, a device with a single Josephson junction was fabricated, in which the junction is positioned at the midpoint of the center conductor. Since the rf current of the odd resonant modes also peaks at the midpoint, the junction exerts maximum influence on these odd resonant modes. On the other hand, the even resonant modes should be essentially unaffected by the presence of the junction, because these modes have a current node at the midpoint. Thus, by measuring both the odd and even modes of the stripline with a

deliberately positioned Josephson junction, the properties of the junction and of the film in which the junction is embedded can be compared [#3]. To proceed with this project, YBCO/YBCoCO/YBCO edge junctions were prepared by Koren *et al.* at the Technion in Israel.

During the 1995–96 year we continued measurements, started during the previous year, of the microwave power dependence of the effective surface impedance of epitaxial $YBa_2Cu_3O_{7-x}$ thin-film resonators containing Josephson edge junctions (JJ). This project will constitute a major portion of the Ph.D. thesis work of Joe Habib. A resistively shunted junction (RSJ) model is being used to account for the power dependence. Improved temperature stability has enabled measurement of the inductance vs. power. The results show that the inductance of the film dominates that of the junction, a finding that is in agreement with the RSJ model. These results were presented at the 1996 Applied Superconductivity Conference in Pittsburgh.

We have also measured, on the same wafer, the dc critical current density J_c to compare with the J_c derived from the rf measurements by fitting the rf results to the RSJ model. We find that the two values of J_c differ, with the rf determined value larger than the dc one. Previously we had found agreement between the rf and dc determinations of J_c when using J_c determined from small junctions. The discrepancy is under investigation, and we believe it is due to flux flow in the dc case which masks the true J_c.

3. Long Junction Effects

We have also begun modeling long junction effects in the striplines containing Josephson junctions by the use of JSIM, a computer program developed at Berkeley for modeling Josephson junction integrated circuits. The JJ for the wide junctions used in our stripline geometry are considered as an array of Josephson junctions fed with a nonuniform current distribution. The modified JSIM program will be applied to interpret the JJ experiments now being carried out. This work is being carried out (starting in June, 1996) by a new student, Chris Lehner, who is an Army Captain on assignment at MIT.

Superconductivity and Related Phenomena in Fullerenes

Three major projects were pursued on the study of superconductivity and related phenomena in C_{60} and doped C_{60}. One project involved writing a large book on fullerenes which was published by Academic Press early in 1996 [#10]. This book contains a chapter on superconductivity in fullerenes. A second project, the Ph.D. thesis of Siegfried Fleischer, concerns measurements on C_{60} and doped C_{60} using femtosecond optics techniques, while a

third project involves study of the dielectric properties of fullerenes with particular regard to the role of oxygen in observed transport phenomena.

The tunable fast optics system which was built the previous year was used to study fast (sub-picosecond) relaxation processes involving the electron-phonon interaction in M_3C_{60} compounds. This system allows for pump-probe measurements at low temperatures and quasi-continuous coherent radiation wavelength tuning from 350 nm to 2.4 μm. One phase of the work, which was initiated during the past year on the study of fast relaxation processes in C_{60}, was completed during the current year. These fast optics experiments were carried out by Siegfried Fleischer on C_{60} films prepared by Boris Pevzner in collaboration with Art Hebard at AT&T Bell Labs (Lucent Technologies). We found that, in contrast with previously published reports, pristine C_{60} films exhibit no ultrafast (0–5 ps) response. To explain our results we carried out a systematic study of the dependence of the relaxation processes on the photon fluence. With this study we were able to reproduce the work of others, showing that previously-reported relaxation effects below 5 ps were due to photodegradation of the samples [#5].

Regarding the pump-probe experiments on superconducting M_3C_{60} (M = K, Rb), samples have now been prepared on sapphire substrates so that the energy of the incident radiation can be suitably dissipated. A large cryostat was constructed to accommodate both the samples (which come sealed in a large tube) and the optics needed to get an optical pulse beam to the sample, and the system is now being tested.

It is well known that the presence of oxygen can change the magnitudes of the various transport observables by several orders of magnitude, strongly affecting the transport mechanism in the normal state as well as the properties in the superconducting state. It is therefore important to understand the mechanism of oxygen diffusion into bulk C_{60} solid (films). To gain such understanding, we have undertaken an investigation of the low-frequency dielectric properties of C_{60} films using a microdielectrometry technique which could be operated over a wide frequency range, 10^{-2} to 10^5 Hz [#6]. On the basis of these observations, a model for a site-hopping mechanism for oxygen diffusion has been developed. This work was carried out by a graduate student Boris Pevzner for his M.S. thesis, and was done in collaboration with Dr. Art Hebard at AT&T Bell Labs where Boris Pevzner had been an MIT coop student.

Personnel Involved with Research Program

The program involves the personnel listed in this section.

- Mildred Dresselhaus - Principal Investigator (10%). Responsible for the research and the direction of all aspects of the program.
- Gene Dresselhaus - Co-principal Investigator (25%). Responsible together with the principal investigator for the research and the direction of all aspects of the program.
- Daniel Oates - Visiting Research Scientist supported 50% by another grant under the same AFOSR program of Dr. Harold Weinstock. Responsible together with the principal investigators for the microwave research on the high T_c thin films.
- Nathan Belk - Research Assistant, Department of Physics. Responsible for microwave studies on striplines as a function of temperature, magnetic field and frequency.
- Siegfried Fleischer - Research Assistant, Department of Electrical Engineering. Responsible for studies on fullerenes using pump-probe femtosecond reflectivity technique.
- Joseph Habib - Research Assistant, Department of Physics. Responsible for microwave studies on striplines containing Josephson junctions.
- Boris Pevzner - Research Assistant, Department of Electrical Engineering. Responsible for sample preparation of films of C_{60} and alkali metal doped C_{60} and for dielectric and photoconductivity studies on fullerenes using a microdielectrometry technique.
- Chris Lehner - Graduate Student, Department of Physics. Responsible for the development of computer modeling for the Josephson junction stripline work.

Invited Talks and Honors

Honors

- Elected President of the American Association for the Advancement of Sciences, February, 1996.

Research Lectures related to work supported by this grant

- Dec. 1, 1995
  MRS talk (NB, JH, & SF), Boston, MA.
- January 28, 1996
  Yokohama Forum (MSD), invited talk, Yokohama, Japan.

- January 31, 1996
  Hitachi Advanced Research Lab. (MSD), invited talk, Saitama Prefecture, Japan.

- February 8, 1996
  Penn. State. U., (MSD), Physics Colloquium, State College, PA.

- February 22, 1996
  Louisiana State U. (MSD), Distinguished Lecture Series, Baton Rouge, LA.

- March 1, 1996
  Columbia U. (MSD), EE Distinguished Lecture Series, New Your City.

- March 1, 1996
  MIT (MSD), Distinguished Lecture Series.

- March 15, 1996
  Tulane U. (MSD), Newcomb Lecture, New Orleans, LA.

- March 25, 1996
  APS Talk (NB), St. Louis, MO.

- April 5, 1996
  Hampton University Physics Colloquium (MSD), Hampton, VA.

- May 8, 1996
  International Conference on Fullerene Chemistry (MSD), Jerusalem, Israel.

- May 9, 1996
  Physics Colloquium (MSD), Weizmann Institute, Rehovot, Israel.

- July 8, 1996
  (MSD) Nanostructure International Conference, Kona, Hawaii.

- August 12, 1996
  Plenary lecture (MSD), International Conference of Raman Scattering, Pittsburgh, PA.

- August 13, 1996
  Plenary lecture (MSD), ERATO Conference of Carbon materials, Chicago, IL.

- September 26, 1996
  (MSD), MIT Physics Colloquium.

New Discoveries, Patents or Inventions

None.

1 Meeting Talks and Posters

- MRS, Boston, Talk
  S. Fleischer, B. Pevzner, D. Dougherty, M. S. Dresselhaus, E. Ippen, and A. F. Hebard, Visible and Near IR Femtosecond Low-Excitation Pump-Probe Studies on C_{60} and Alkaline Doped C_{60} Films, MRS Abstracts, page 739 (1995).

- MRS, Boston, Poster
  Y. M. Habib, D. E. Oates, G. Dresselhaus, and M. S. Dresselhaus, DC Magnetic Field Effects on the Microwave Power Dependence of $YBa_2Cu_3O_{7-\delta}$ Thin Film Josephson Edge Junctions, MRS Abstracts, page 217 (1995).

- MRS, Boston, Poster
  Nathan Belk, D. E. Oates, D. A. Feld, G. Dresselhaus, and M. S. Dresselhaus, Analysis of Frequency Dependence of Vortex Dynamics in $YBa_2Cu_3O_{7-\delta}$ Thin Films in a DC Magnetic Field, MRS Abstracts, page 189 (1995).

- APS, St. Louis, Talk
  Nathan Belk, D. E. Oates, M. S. Dresselhaus, and G. Dresselhaus, Nonlinear Microwave Flux Dynamics: Role of Pinning and Power Dependence, Bull. Am. Phys. Soc. **41**, 283 (1996).

- MRS, San Francisco, Talk
  D. E. Oates, Nathan Belk, G. Dresselhaus, and M. S. Dresselhaus, Nonlinear Microwave Flux Dynamics: Relationship between Pinning and Power Dependence, MRS Abstracts, page 308 (1996).

- Applied Superconductivity Conference, Pittsburgh, Poster.
  Y. M. Habib, D. E. Oates, G. Dresselhaus, and M. S. Dresselhaus, "Power dependence of microwave Z_s in high-T_c Josephson junctions: measurements and modeling."

Publications

1. N. Belk, D. E. Oates, D. A. Feld, G. Dresselhaus, and M. S. Dresselhaus, Frequency and temperature dependence of the microwave surface

impedance of $YBa_2Cu_3O_{7-\delta}$ thin films in a dc magnetic field: Investigation of vortex dynamics, Phys. Rev. B **53**, 3459–3470 (1996).

2. D. E. Oates, P. P. Nguyen, Y. Habib, G. Dresselhaus, M. S. Dresselhaus, G. Koren, and E. Polturak, Microwave power dependence of $YBa_2Cu_3O_7$ thin film Josephson edge junctions, Appl. Phys. Lett. **68**, 705 (1996).

3. D. E. Oates, P. P. Nguyen, G. Dresselhaus, M. S. Dresselhaus, G. Koren, and E. Polturak, Nonlinear surface impedance of $YBa_2Cu_3O_7$ thin films: measure, modeling and effects in devices, Journal of Superconductivity **8**, 725 (1995).

4. M. S. Dresselhaus and B. Pevzner. Recent advances in the applications of fullerenes, In *Extended Abstracts of the 21st Century Forum*, 1996. (Jan 27–29, 1996, Yokohama, Japan.)

5. S. B. Fleischer, B. Pevzner, D. J. Dougherty, E. P. Ippen, M. S. Dresselhaus, and A. F. Hebard, Phototransformation in visible and near-IR femtosecond pump-probe studies of C_{60} films, Appl. Phys. Lett. **69**, 296–298 (1996).

6. B. Pevzner, A. F. Hebard, and M. S. Dresselhaus, Role of molecular oxygen and other impurities in the electrical transport and dielectric properties of C_{60} films, Phys. Rev. B (1996). (Submitted 06/06/96: MS Code: BT5733.)

7. Y. M. Habib, D. E. Oates, G. Dresselhaus, and M. S. Dresselhaus, Power dependence of microwave Z_s in high-T_c Josephson junctions: measurements and modeling, IEEE Trans. Appl. Superconductivity (1996). Proceedings of the Applied Superconductivity Conference.

8. Nathan Belk, D. E. Oates, D. A. Feld, G. Dresselhaus, and M. S. Dresselhaus, Analysis of the nonlinear dynamics of vortices in $YBa_2Cu_3O_{7-\delta}$ thin films in a dc magnetic field, Phys. Rev. B (1996). in preparation.

9. Nathan Belk, Electronic Transport and Magnetic Properties of Disordered High-T_c Materials, Ph.D. Thesis, Department of Physics, Massachusetts Institute of Technology, September, 1996.

10. M. S. Dresselhaus, G. Dresselhaus, and P. C. Eklund, in *Science of Fullerenes and Carbon Nanotubes*, (Academic Press, New York, NY, 1996).